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Experimental Verification of the Computer Program CANOPY by the Static Testing of a Continuous Miner Canopy

A Supplement to Bureau of Mines Information Circular 8546

UNITED STATES DEPARTMENT OF THE INTERIOR
U.S. Mining Enforcement and Safety Administration
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UNITED STATES. MINING ENFORCEMENT AND SAFETY ADMINISTRATION.

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By Stephen G. Sawyer, Darryl K. Brogan, John L. Dahle, and George J. Karabin, Jr.
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UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

Mining Enforcement and Safety Administration
James M. Day, Administrator

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EXPERIMENTAL VERIFICATION OF THE COMPUTER PROGRAM CANOPY BY THE STATIC TESTING OF A CONTINUOUS MINER CANOPY

A Supplement to Bureau of Mines Information Circular 8546

by

Stephen G. Sawyer,[1] Darryl K. Brogan,[1] John L. Dahle,[2] and George J. Karabin, Jr.[1]

ABSTRACT

The Roof Control Group, Pittsburgh Technical Support Center, Mining Enforcement and Safety Administration, conducted a full scale test on a continuous miner canopy to verify the accuracy of the computer program CANOPY previously published in Bureau of Mines Information Circular 8546. The commercially available canopy was instrumented at selected locations with strain and displacement gages, and point-loaded simultaneously at 16 places. Elastic strains and displacements were recorded for a variety of load levels during both loading and unloading. The computer program analyzed the full scale test using the physical, geometrical, and sectional properties measured for the canopy's structural members. In general, the stresses and displacements calculated by the program agreed within 5 percent of those measured experimentally.

INTRODUCTION

In all coal mines, substantially constructed cabs and canopies will be required on electric face equipment, including shuttle cars, to protect the operators of such equipment from falls of roof, face, and rib (1).[3] These cabs and canopies must be certified by a State registered, professional engineer as capable of elastically supporting the uniform load required in the amended Federal Coal Mine Health and Safety Act of 1969 (1). Certifications can be based upon engineering calculations.

The Bureau of Mines has published a computer program titled CANOPY (2) by which cabs and canopies can be analyzed, designed, and certified. To verify the accuracy of this computer program, a commercially available continuous miner canopy was subjected to a full scale test and experimental results were compared with computer calculations.

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[1] Civil engineer, Roof Control Group.
[2] Mechanical engineer, Roof Control Group.
[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

The purpose of this report is to document the experimental tests conducted by MESA and to show the correlation of test data with results calculated by CANOPY. In these tests the continuous miner canopy was instrumented at various locations with strain and displacement gages and point-loaded simultaneously at 16 places. Elastic strains and displacements were recorded for a variety of load levels during both loading and unloading. To assist others interested in conducting similar tests to verify engineering analyses on cabs or canopies, a detailed description of the experimental approach is given.

ACKNOWLEDGMENTS

The continuous miner canopy was donated by Lee-Norse Company, Charleroi, Pa. The Civil Engineering Department, University of Pittsburgh, Pittsburgh, Pa., instrumented and tested the canopy in their structural engineering laboratory. The authors thank William Pascoe, mining engineering technician, Roof Control Group, Pittsburgh Technical Support Center, for his help in preparing this report.

OUTLINE OF EXPERIMENTAL TEST AND ANALYTICAL CALCULATIONS

The experimental phase of this study involved the loading of a commercially available continuous miner canopy and the monitoring of the induced strains and displacements at various points on the structure's top. Equal point loads were applied at intervals at 16 locations. Bending strains were recorded at the centerline of two members, and the vertical displacements of the end points and centerline of a member were measured.

Prior to testing, preliminary work was done with the structural tubing of which the canopy was constructed. The tubing's physical properties (Young's modulus, yield stress, tensile stress, and percent elongation) were determined from coupon tests. A third-point bending test (the point loading of a simply supported section of structural tubing at its third points) was employed to measure the moments of inertia. The bending test is especially important since allowable variations in cross-sectional dimensions (3) can affect section properties as much as 15 percent.

Using the measured dimensional, physical, and mechanical properties, CANOPY calculated the stresses and displacements at the instrumented points. The analytically calculated stresses were transformed to strains and along with displacements were compared with similar quantities from the experimental test.

COUPON TESTS

To properly analyze any structure, the physical properties of the materials composing the structure must be determined. Yield stress (σ_y), ultimate stress (σ_u), modulus of elasticity (E), and percent elongation (D_e), can be calculated from data gathered in a simple tension test.

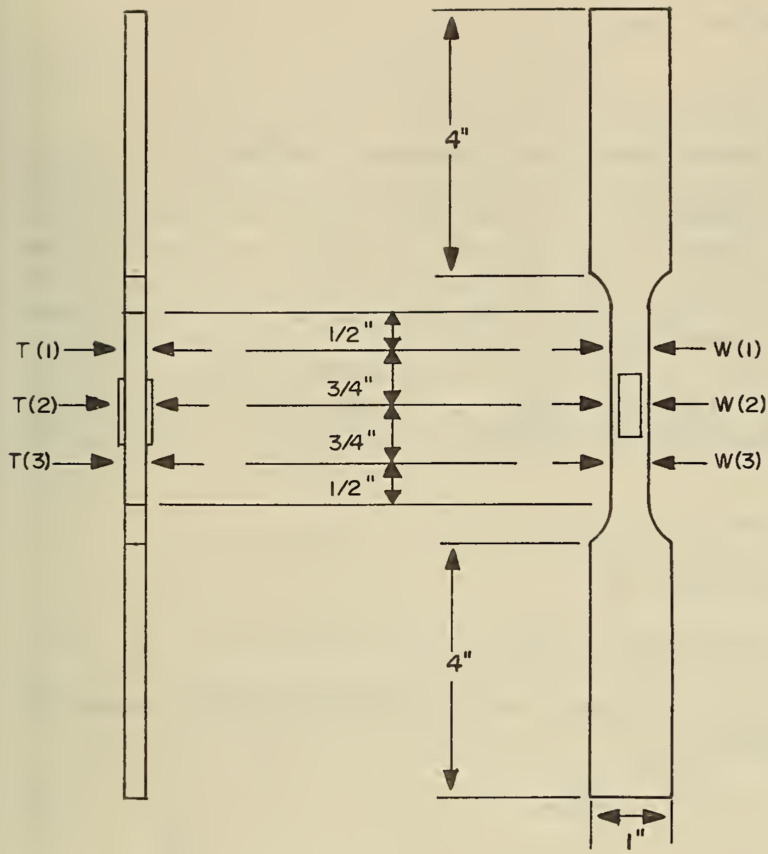


FIGURE 1. - Geometry of tensile coupon.

Two coupons were obtained from the tubing of which the canopy was constructed and loaded by a universal testing machine in accordance with ASTM designation A370-65 (4) testing procedures. Figure 1 illustrates the geometry of the coupons where the parameters W(i) and T(i) are the width and thickness, respectively, at various points along the gage length. The area used to calculate stress was the mean area over the gage length and is given by:

$$\bar{A}_g = \frac{1}{3} \sum_{i=1}^{3} [T(i)W(i)], \quad (1)$$

where $T(i) \simeq 0.25$ in and $W(i) \simeq 0.50$ in.

In accordance with the aforementioned ASTM testing procedure, strain gages (Micro Measurement EA-06-250BG-120)[4] and a 2-inch gage length, surface-mounted extensometer were attached to the coupon to determine an accurate stress-strain relationship in both the elastic and post yield ranges. Prior to testing a 2-inch gage length was scribed on the coupon so that the elongation of the specimen at failure could be measured with a set of vernier calipers.

As the coupons were loaded, the uniaxial strain was recorded at various intervals and the deformation indicated by the extensometer was plotted. After the specimens failed, the maximum load was recorded and the change in length of the scribed 2-inch gage length was measured.

The modulus of elasticity of the specimens is determined by:

$$E = \frac{1}{m\bar{A}_g} \sum_{i=1}^{m} \frac{P(i)}{\varepsilon(i)}, \quad (2)$$

[4]Reference to specific equipment does not imply endorsement by the Mining Enforcement and Safety Admininistration.

where E = modulus of elasticity, psi,

$P(i)$ = applied load, lb,

$\overline{A}_g$ = average cross-sectional area over the gage length, in^2,

$\varepsilon(i)$ = measured strain, in/in,

and m = number of readings.

The percent elongation is calculated as:

$$D_e = \frac{l_f - l_o}{l_o} \times (100), \tag{3}$$

where D_e = percent of elongation,

l_f = final scribed gage length, in,

and l_o = original scribed gage length, in.

The yield stress was found by employing the 0.2 percent offset method (5) while the ultimate stress is defined as:

$$\sigma_\mu = P_\mu / \overline{A}_g, \tag{4}$$

where σ_μ = ultimate stress, psi,

P_μ = ultimate load of coupon, lb,

and $\overline{A}_g$ = mean area of the cross section, in^2.

The physical properties were calculated by the preceding equations and their average values for both coupons are summarized below:

$$E = 29{,}000{,}000 \text{ psi}$$

$$\sigma_y = 70{,}000 \text{ psi}$$

$$\sigma_\mu = 81{,}500 \text{ psi}$$

$$D_e = 15 \text{ percent.}$$

SECTION PROPERTIES TEST

In addition to the physical properties determined in the coupon tests, the moment of inertia about each bending axis of a structural member must be accurately defined to effect a truer comparison of the computer and experimental results. Handbook values for I_y and I_z may not be exact for a given section since variations in cross sectional dimensions occur during the

rolling process. Accordingly, third-point bending tests were conducted to determine the true moments of inertia.

A 35-inch length of the rectangular tubing of which the canopy was constructed was loaded in a universal testing machine about each axis, as illustrated in figure 2. To accurately monitor the strain at the outer fibers due to bending, two Micro Measurement EA-06-250BG-120 strain gages were mounted on each of the four sides of the tubing, as shown in figure 3. Also indicated in this figure are the Wheatstone bridge configurations employed to monitor the bending strains as the beam was loaded about each axis. These full Wheatstone bridges insure that only bending strains about each axis are measured. The free body diagram of figure 4 illustrates both the loading conditions and the restraints of the member when loads of P/2 are applied at points L/3 from the end supports. The equation for the bending moment (M_b) at the center of the span is:

$$M_b = \frac{PL}{6}, \tag{5}$$

where P = total applied load, lb,

and L = length of span, in.

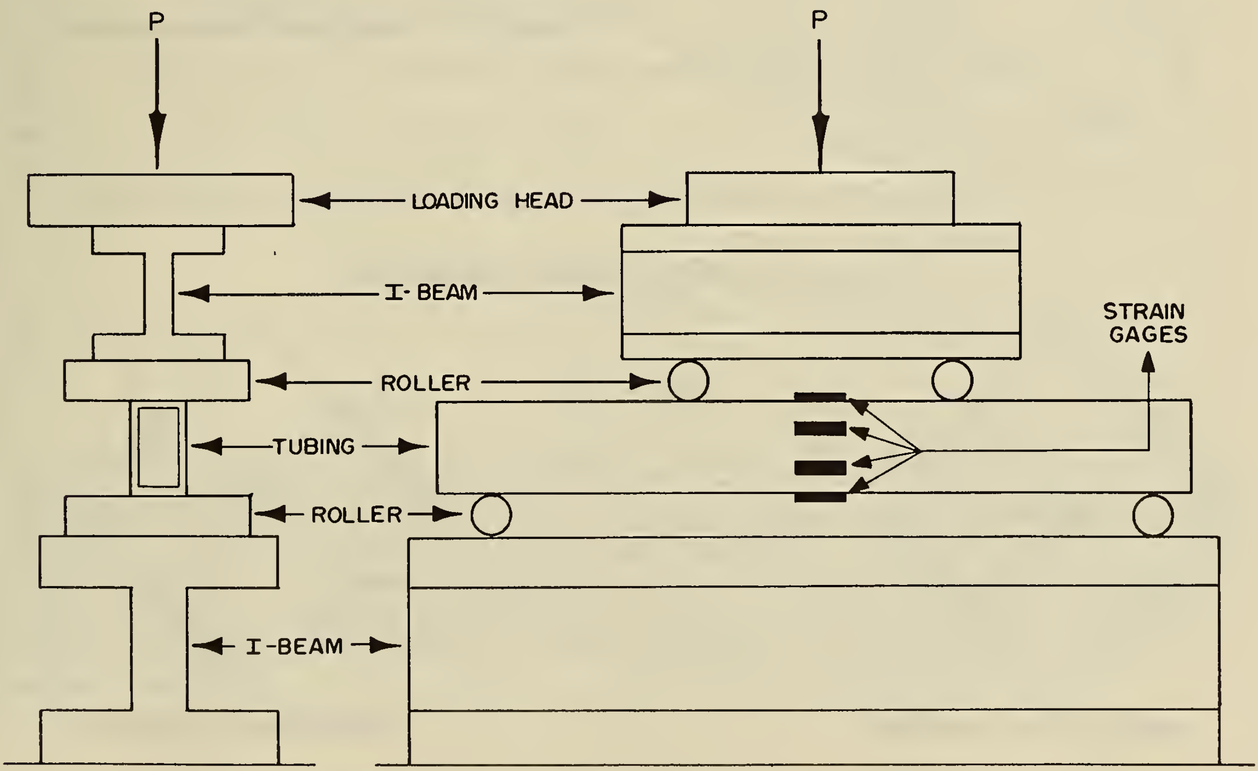
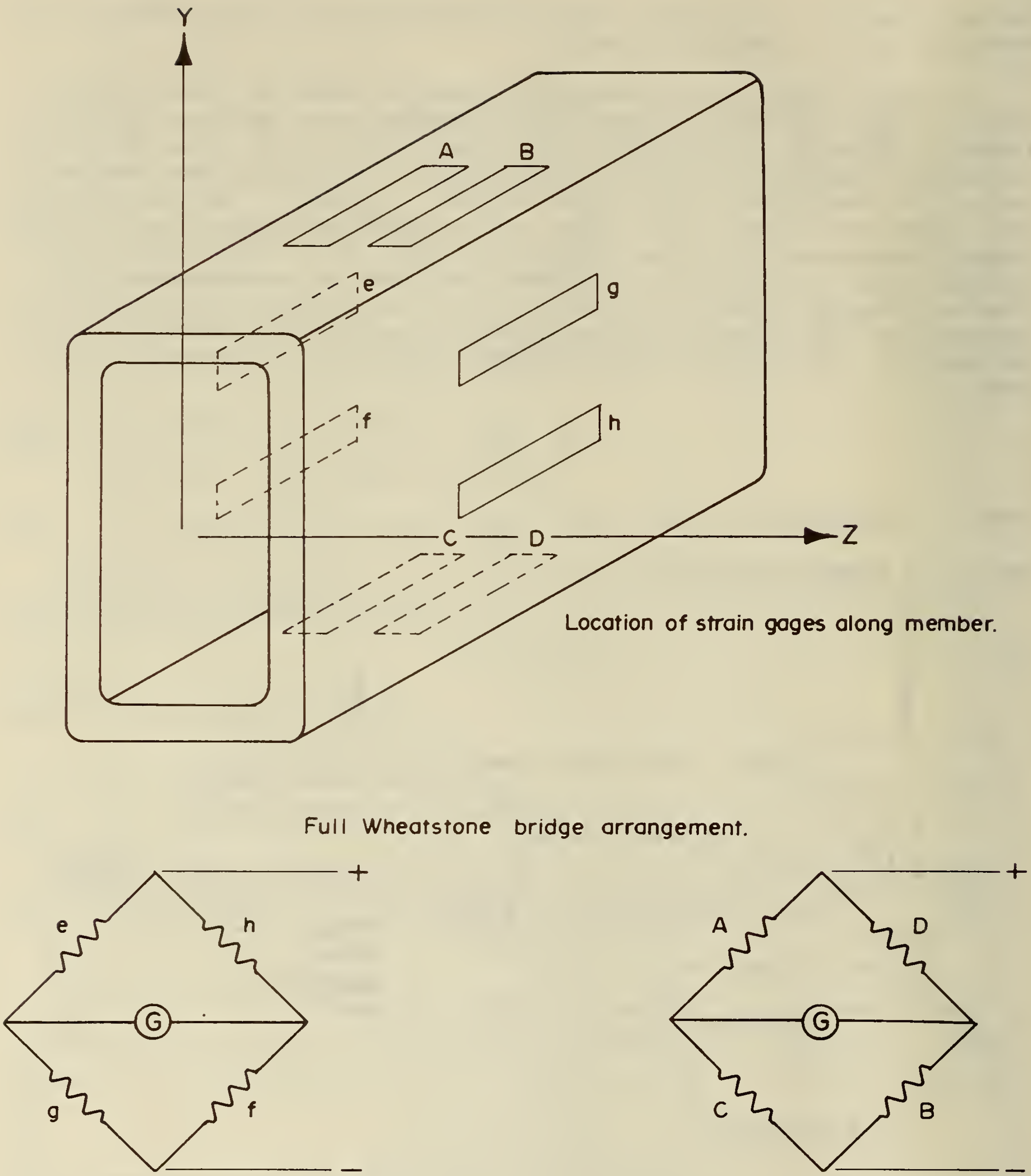


FIGURE 2. - Third-point bending test arrangement.



Loading in the Z direction.

Loading in the Y direction.

FIGURE 3. - Location of strain gages on test section.

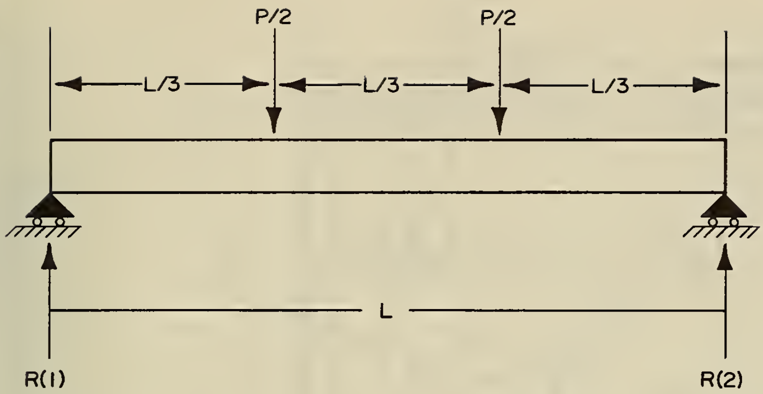


FIGURE 4. - Free body diagram of third-point bending test shown in figure 2.

The beam was loaded about each axis to a variety of loads (within the elastic range) and the corresponding bending strains were recorded. Since the modulus of elasticity has been determined from the coupon tests, the following equation was employed to determine the moment of inertia of the section:

$$I = \frac{c}{nE} \sum_{i=1}^{n} \frac{M_b(i)}{\varepsilon(i)}, \quad (6)$$

where I = moment of inertia about Z or Y axis, in^4,

$M_b(i)$ = bending moment applied by load $P(i)$, in-lb,

c = distance from neutral axis to outer fibers, in,

E = modulus of elasticity, psi,

$\varepsilon(i)$ = recorded bending strain due to load $P(i)$, in/in,

and n = number of applied loads.

The section properties determined from equation 6 were:

$$I_z = 1.18 \text{ in}^4$$

$$I_y = 0.55 \text{ in}^4.$$

CANOPY TEST

Presented in figure 5 is a general layout of the canopy tested in this study. The canopy is constructed of 2-1/2-inch by 1-1/2-inch, 1/4-inch thick, rectangular structural tubing with a 1/4-inch plate welded on the bottom of the structure's five legs. The plate was employed to restrain the leg's horizontal movement. Sixteen hydraulic rams were used and were all connected by a manifold system that insured identical loads were applied by each ram. Figure 6 illustrates the positions of the hydraulic rams on the top of the canopy.

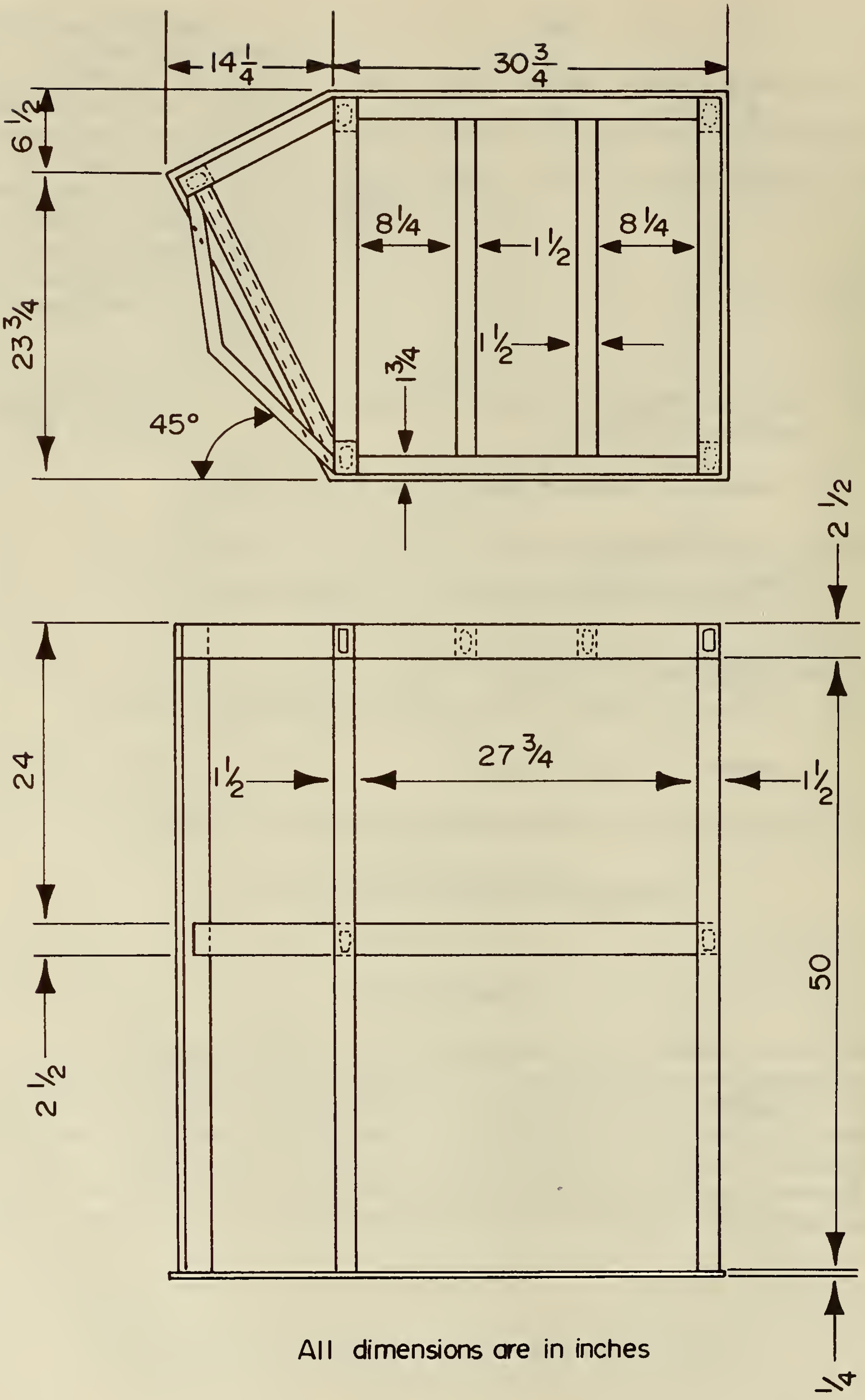


FIGURE 5. - Layout of canopy tested in investigation.

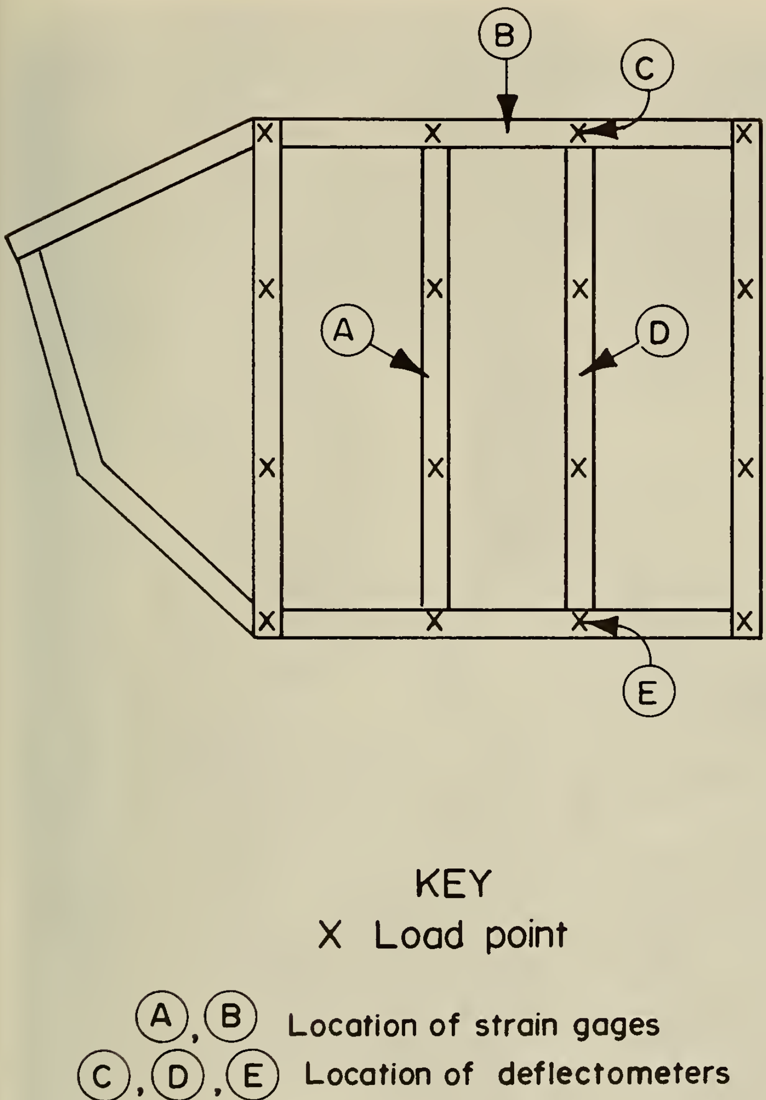


FIGURE 6. - Locations of hydraulic rams, strain gages, and deflectometers on top of canopy.

Also shown in figure 6 are the locations for the BLH Electronic SR4-A1 strain gages and the displacement dial gages (or deflectometers) that instrumented the canopy. At points designated as A and B in this figure, strain gages were mounted on the top and bottom of the members and connected to a strain gage readout system. A full Wheatstone bridge was utilized which enabled pure bending strains to be recorded. The gages placed at A and B are at the centerline of an outside and inside structural member, respectively. Points identified as C, D, and E in figure 6 were the positions of vertical deflectometers that had sensitivities of 0.001 inch. These locations were chosen to monitor the behavior of a cross beam in the canopy's top.

Figures 7 and 8 depict the overall test setup. To the right of figure 7 is the loading console of the 200,000-pound universal testing machine in which the canopy was tested. The applied load was distributed as 16-point loads on the structure's top by the 16 identical hydraulic rams. Figure 9 shows how the rams were placed on the top of the canopy. The manifold system which was employed to give equal ram loads is shown in this figure as well as in figure 7. One-inch spacers were placed underneath the four central rams and half-inch spacers were placed underneath the remaining rams not over a column. The four rams over the columns had no spacers. The use of these spacers permitted differential deflection of 3 inches with rams that had a maximum travel of 2 inches.

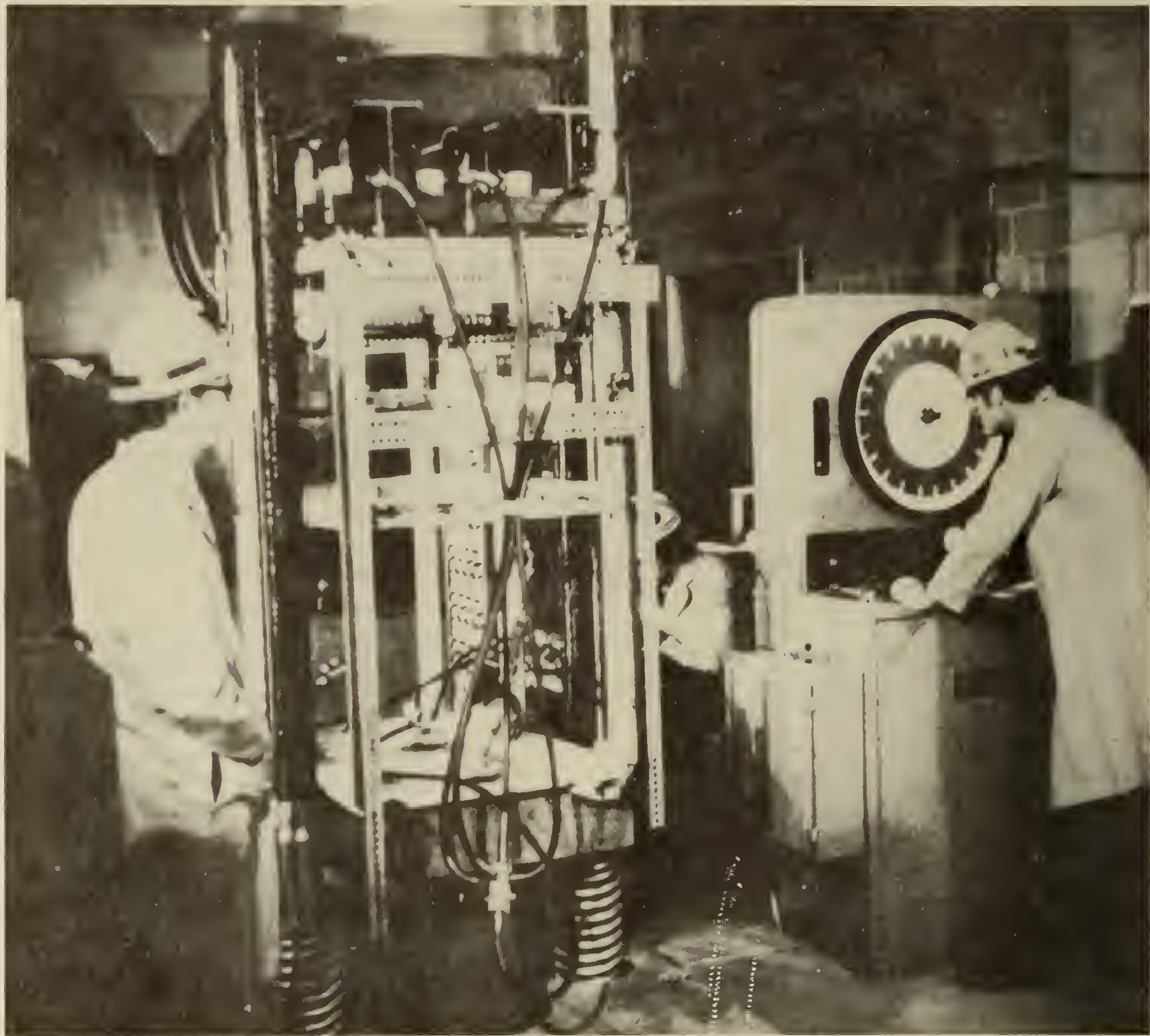


FIGURE 7. - Overall view of setup for canopy test.

In figure 10 two of the displacement dial gages or deflectometers are shown. These gages were supported by a perforated angle frame. Behind the center dial gage in figure 10 is the strain gage located at the center of the top beam; this strain gage is at location A depicted in figure 3.

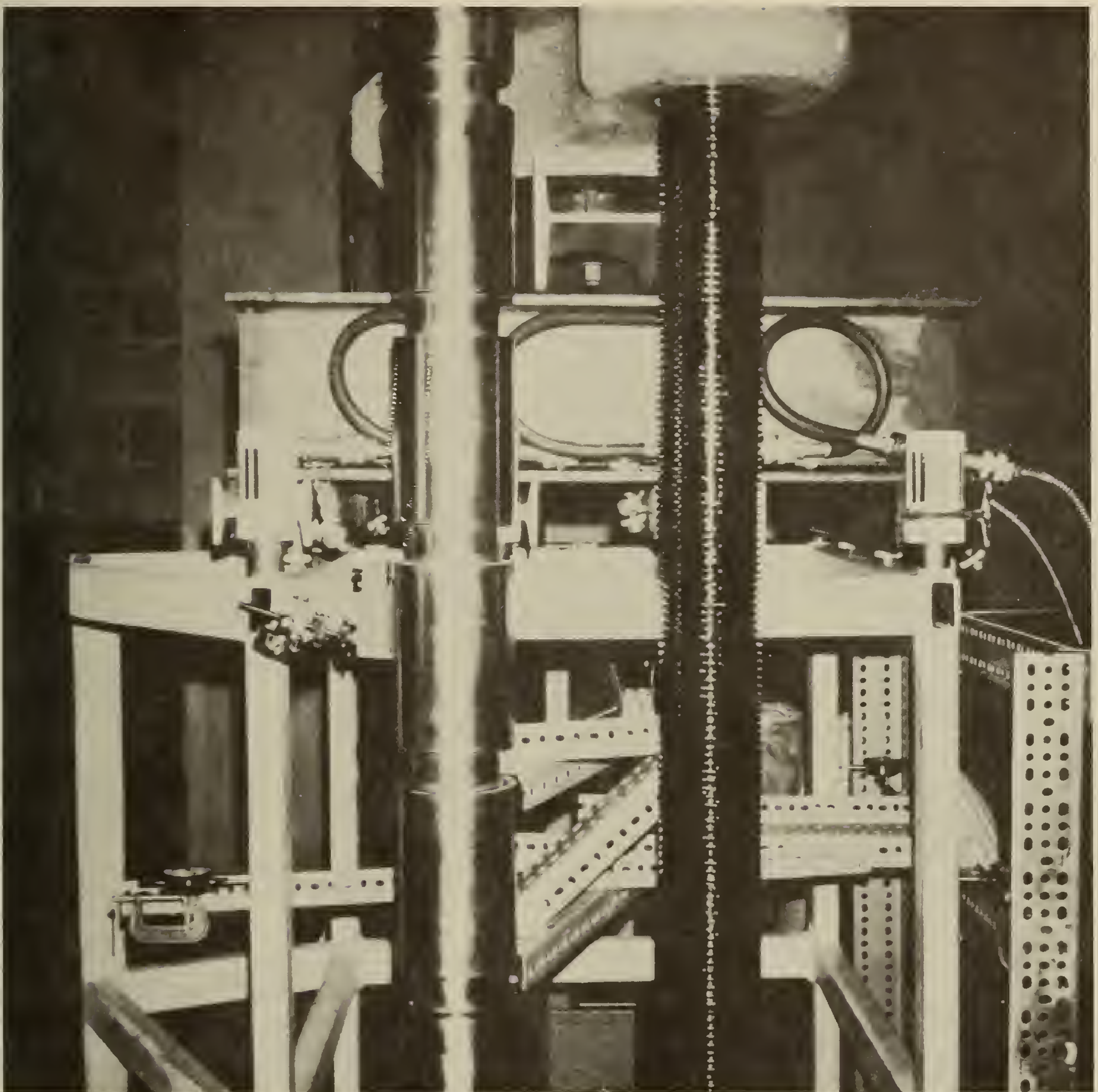


FIGURE 8. - Side view of test canopy.

FIGURE 9. - Placement of hydraulic rams on the top of the canopy.

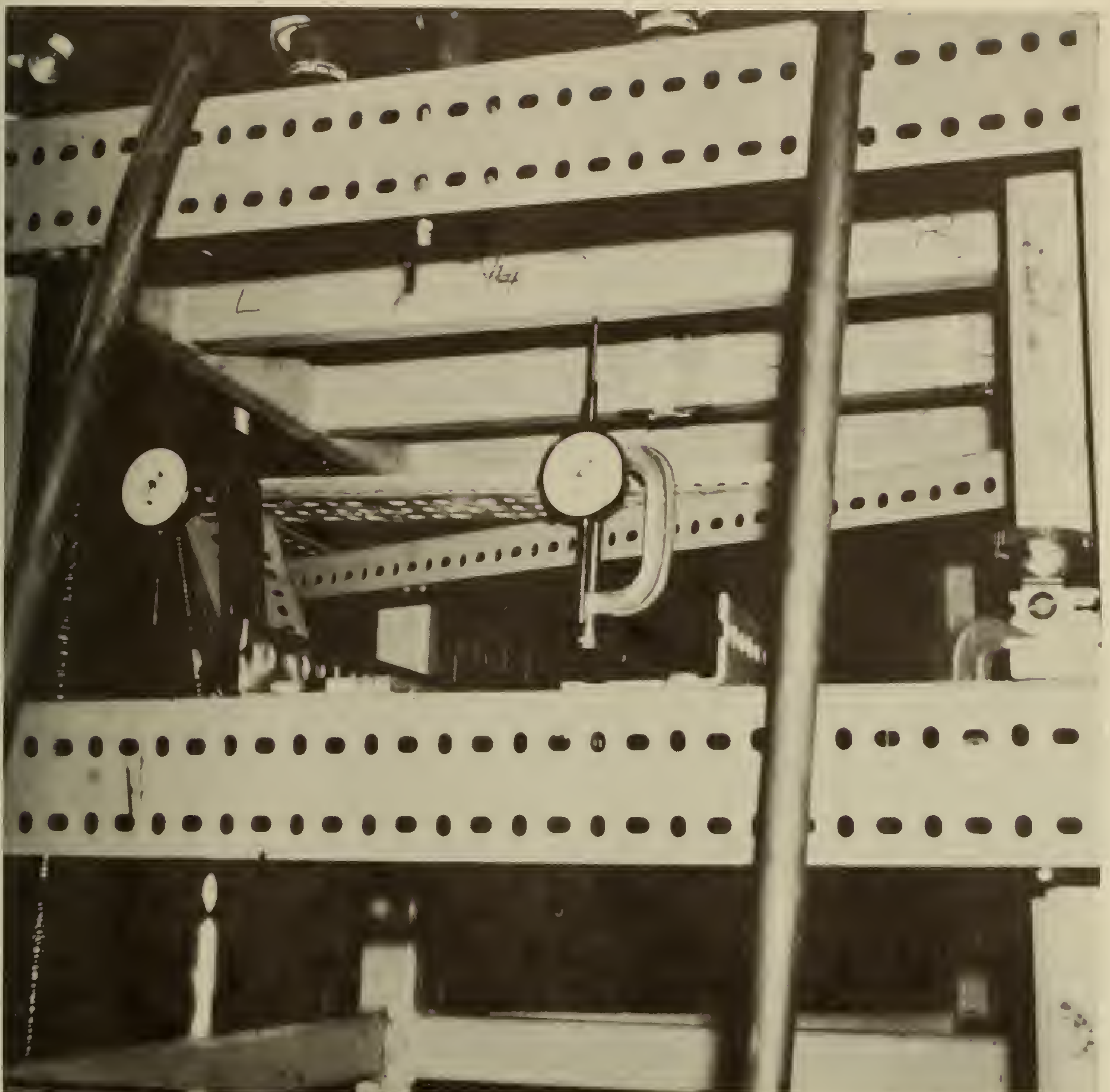


FIGURE 10. - Two displacement dial gages monitoring the deflection of the canopy's top.

The load was applied in intervals by the testing machine, up to a maximum of 33,000 lb. Prior to testing, a preliminary analysis of the entire canopy was made using the computer program which indicated that the canopy's elastic strength was well in excess of 33,000 lb. Deflectometer and strain gage readings were made at various levels during both loading and unloading. Presented in figures 11 and 12 are the experimental data collected for a load and unload cycle conducted on the subject canopy.

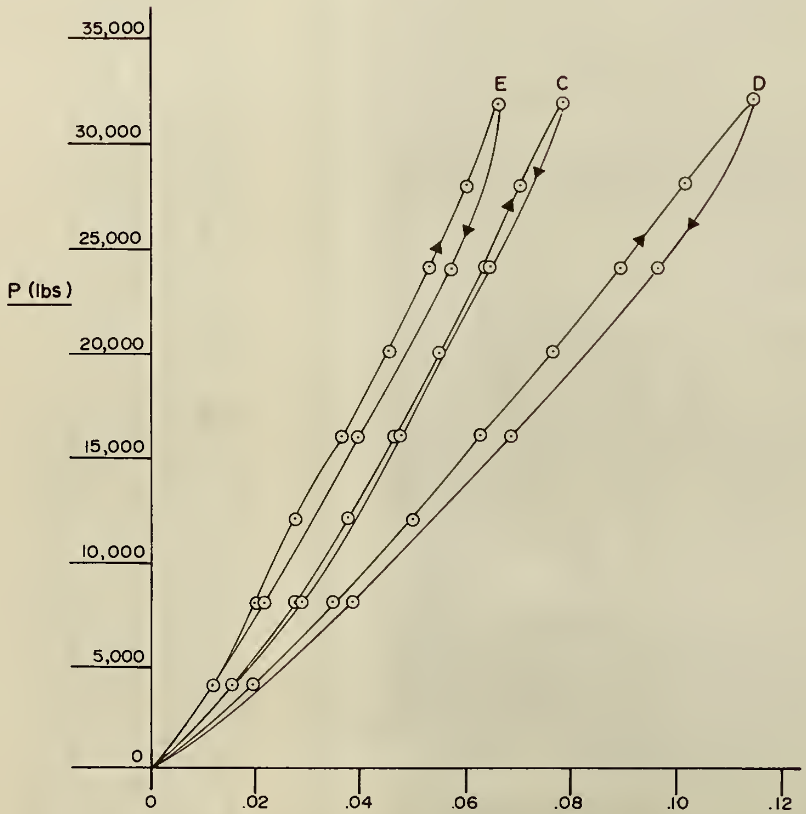


FIGURE 11. - Experimental load-deflection values for points C, D, and E on test canopy.

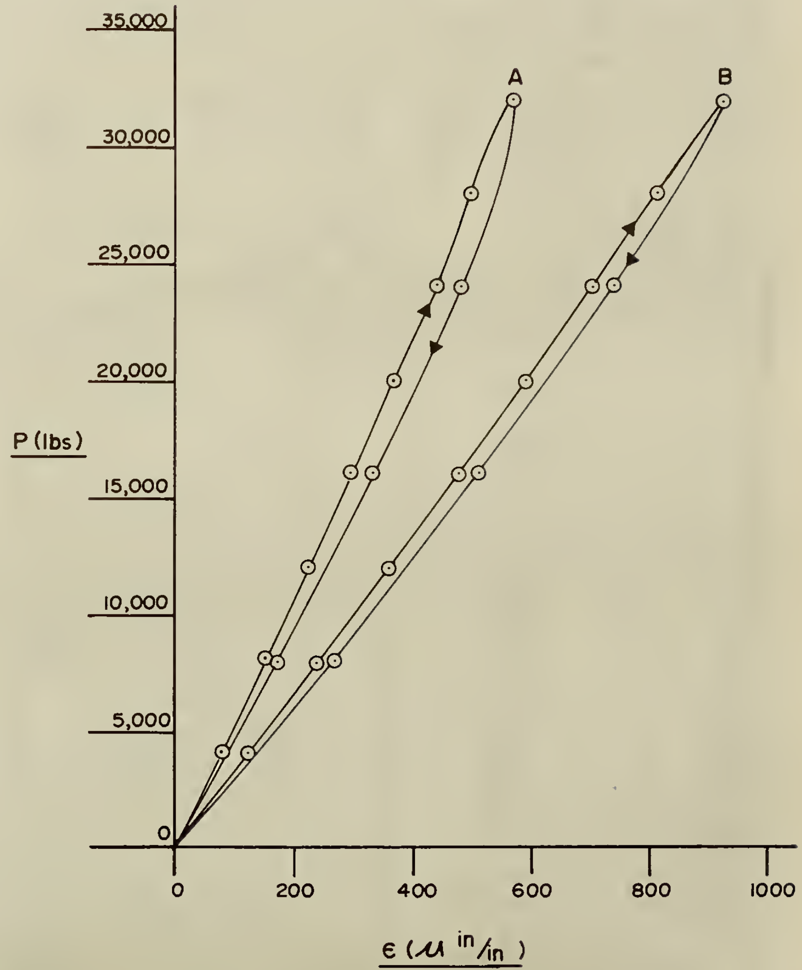


FIGURE 12. - Experimental load-strain values for points A and B on test canopy.

COMPUTER ANALYSIS

The canopy test presented in the previous section was analyzed by the computer program CANOPY (2). CANOPY, which is based upon the three-dimensional (or space) frame stiffness method, computes the moments and forces at the ends of each member in the space frame, and calculates and prints out the displacements of the joints and the stresses in the members of the space frame. In using this computer program the initial step is the identification of the canopy's structural members and its joints or nodes. An origin is arbitrarily placed at any node of the canopy and represents the origin of the global coordinate system, X_s, Y_s, Z_s. This system must be right-handed preferably with Y_s axis vertical. The nodes are identified numerically and the spatial coordinates of each node are calculated from this origin. Every member has a node on both ends and is also identified numerically. Figures 13 and 14 show the numerical identification of the members and nodes, respectively, for the test canopy. Node 13 was chosen as the origin of the global coordinate system, as shown in figure 14. There are a total of 31 nodes and 40 members.

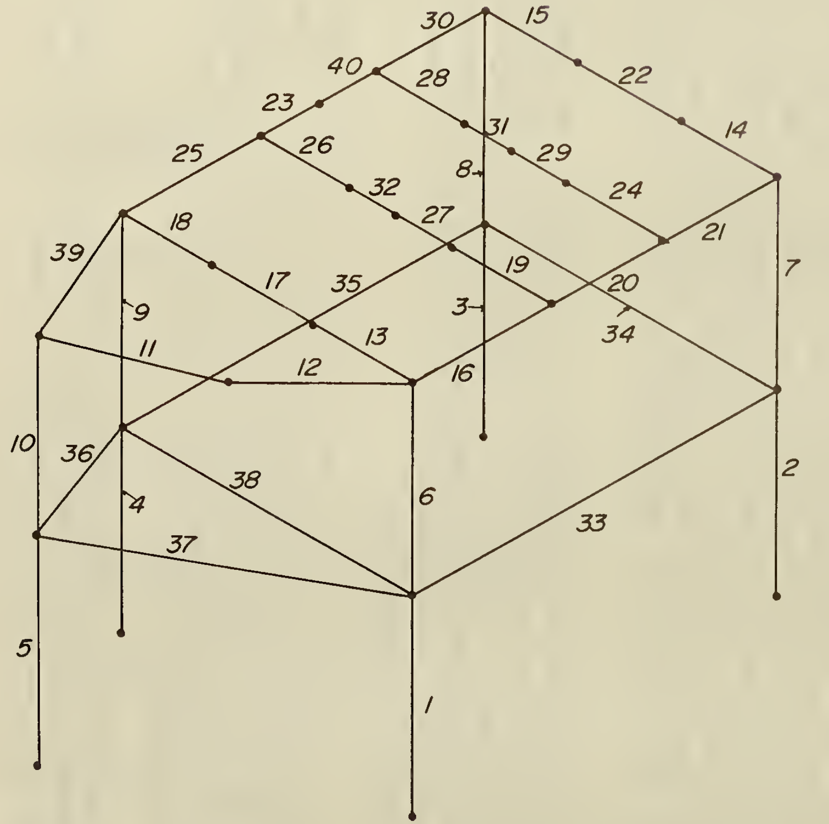
Placement of a node is critical in that a node must be located at every structural joint, such as nodes 1, 6, and 13 in figure 14. Also, there must be a node wherever an external point load is to be applied. Figure 15 shows the 16 equal load points applied to the canopy.

If the displacement or strain at a particular position on the canopy is of concern, then a node must be placed at that position. Such is the case where the deflectometers and the strain gages were used. For the test, deflectometers were placed at the location of nodes 23, 27, and 12, as shown in figure 14, or at locations C, D, and E, respectively, as shown in figure 6. The strain gages were placed on the test canopy at locations A and B as shown in figure 6. Nodes were located at these points and their member end actions were printed out by the addition of an appropriate card to the published program.

In the computer program the nodes can be restrained in any combination of the three coordinate displacements and the three rotational displacements. For the test, canopy nodes 1 through 4 were restrained from displacing in all directions but were allowed to rotate about each axis. Node 5 was allowed to rotate and move vertically because it was not supported by the base of the testing machine during the actual test.

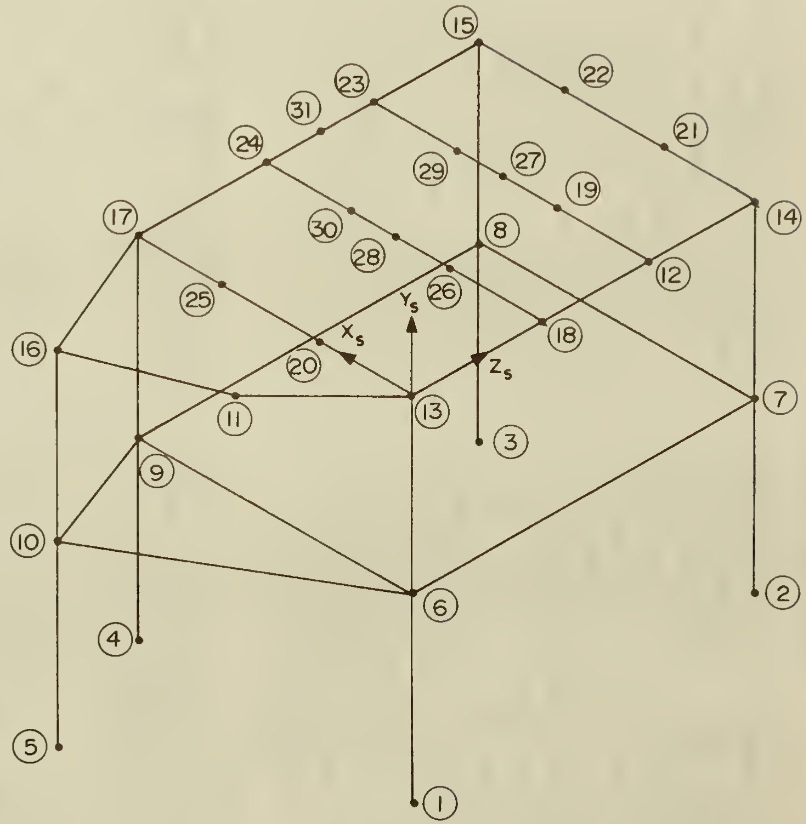
After the nodes and members have been numbered, the next step is to identify the material and sectional properties of the members. Young's modulus (E), shear modulus (G), and yield strength (YSTRS) are entered into the computer program. Young's modulus and the yield strength were determined experimentally by the tensile coupon tests. The shear modulus was calculated using Young's modulus and an assumed Poisson's ratio of 0.285.

Sectional properties can be put into the computer directly for all types of structural members or can be automatically calculated by the computer for structural tubing; pipe; circular, square, or rectangular bars; and I beams.



40 Members

FIGURE 13. - Numerical identification of structural members in test canopy.



(31) Nodes

FIGURE 14. - Numerical identification of nodes in test canopy and location of global coordinate axes.

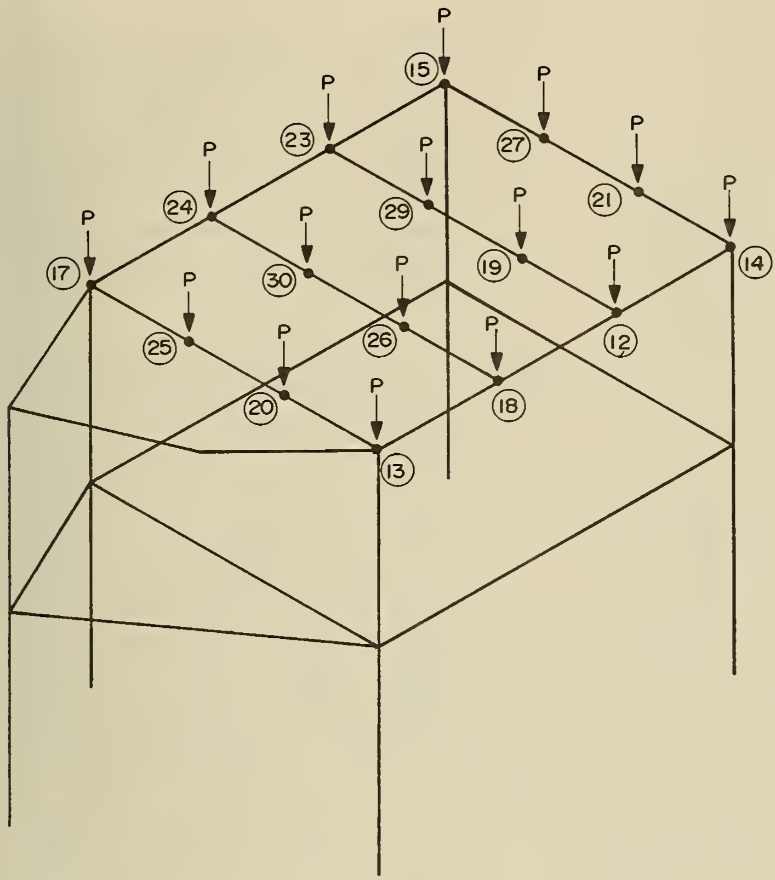


FIGURE 15. - Location of 16 point loads on test canopy.

Sectional properties are calculated with respect to right-handed, member-oriented axes, X_m, Y_m, and Z_m. The X_m axis is located along the length and through the centroid of the member, and has its origin at the node with the smaller numerical identifier. The Z_m axis lies in the X_s-Z_s plane except for those members parallel to the Y_s axis, in which cases it is in the direction of the Z_s axis.

When the sectional properties of a member are to be calculated within the computer program, the user puts into the computer the member's cross-sectional height (H), width (B), web thickness (TW), and flange thickness (TF). From this input the program calculates the principal moments of inertia (IYP and IZP) and the torsion constant (IXP) with respect to axis Y_m, Z_m, and X_m, respectively; cross-sectional area (AXP); distances from the neutral axes to extreme fibers (ACXP, ACYP, and ACZP); and shape factor (FP). When defining the sectional properties of a member directly, the user enters AXP, IXP, IYP, IZP, FP, and the Y_m-Z_m coordinates of up to four points on the member's cross section at which the maximum bending stresses could occur. The coordinates of these points are given by ACZM(i) (Y_m coordinate) and ACYM(i) (Z_m coordinate), i = 1, 2, 3, 4.

To accurately model the canopy test, the following sectional properties were entered for the canopy's tubing:

$$AXP = 1.48 \text{ in}^2,$$

$$IXP = 1.16 \text{ in}^4,$$

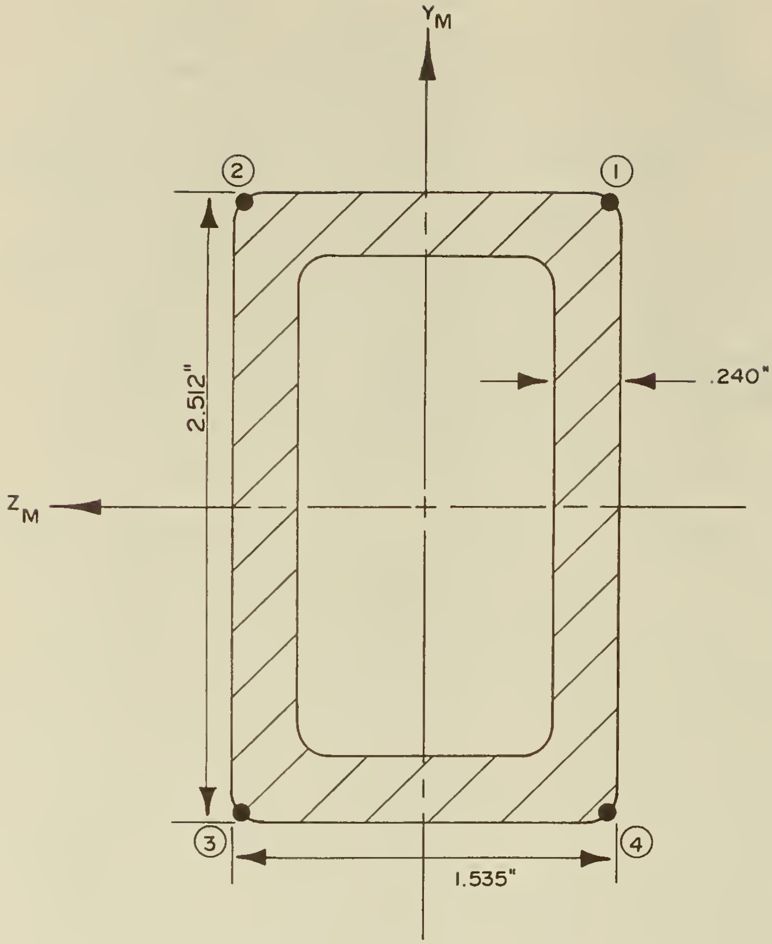
$$IYP = 0.55 \text{ in}^4,$$

$$IZP = 1.18 \text{ in}^4,$$

$$ACXP = 0.82 \text{ in},$$

and

$$FP = 2.38.$$



	ACYM	ACZM
(1)	- 0.767"	1.256"
(2)	0.767"	1.256"
(3)	0.767"	- 1.256"
(4)	- 0.767"	- 1.256"

FIGURE 16. - Location of four points on cross section of rectangular tubing at which highest bending stress could occur.

IYP and IZP were determined in the third-point bending test while the remaining properties were calculated using the measured dimensions of the tubing. The four points of highest bending stress are located and listed in figure 16.

Once the aforementioned information is entered, CANOPY computes and prints out the six nodal displacements: three translations and three rotations. Since this is an elastic analysis, all nodal displacements will be a linear function of the applied load. Because the displacement of each node is known for the applied load, a graph of displacement versus applied load can be drawn through this point and the origin. This was done for the vertical displacements of the three locations D, C, and E (where the deflectometers were located), as shown in figure 17.

A plot similar to figure 17 can be drawn for the load versus the bending strain for points A and B at which strain gages were located in the test canopy. The end moments for these nodal points were printed out. The formula below gives the bending strain at these points as follows:

$$\varepsilon_b = \frac{M_e c}{I_z E}, \qquad (7)$$

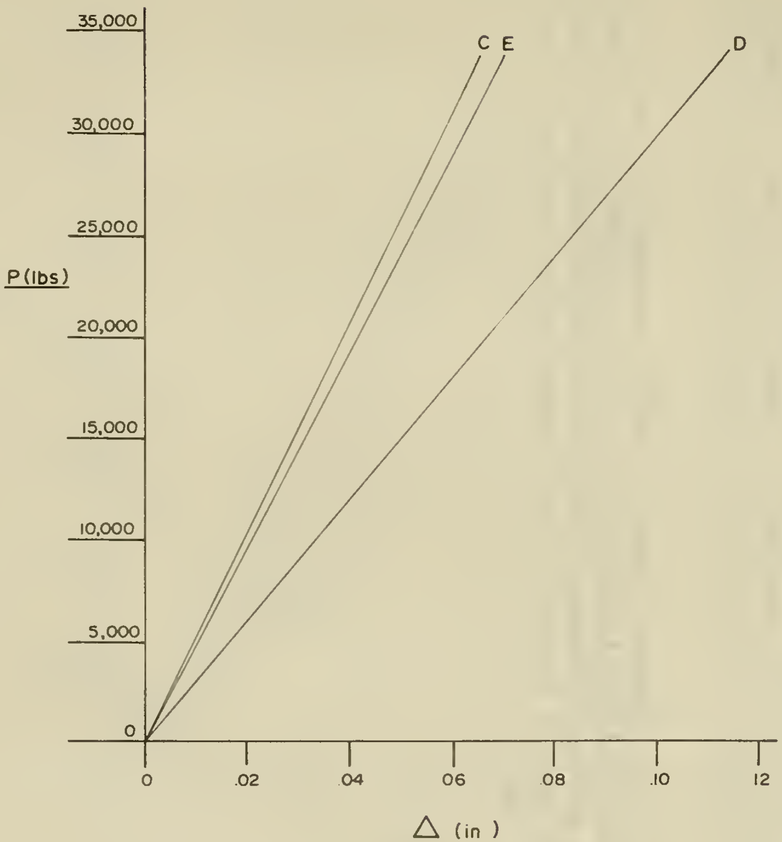


FIGURE 17. - Computer calculated load vertical displacement lines for points C, D, and E on test canopy.

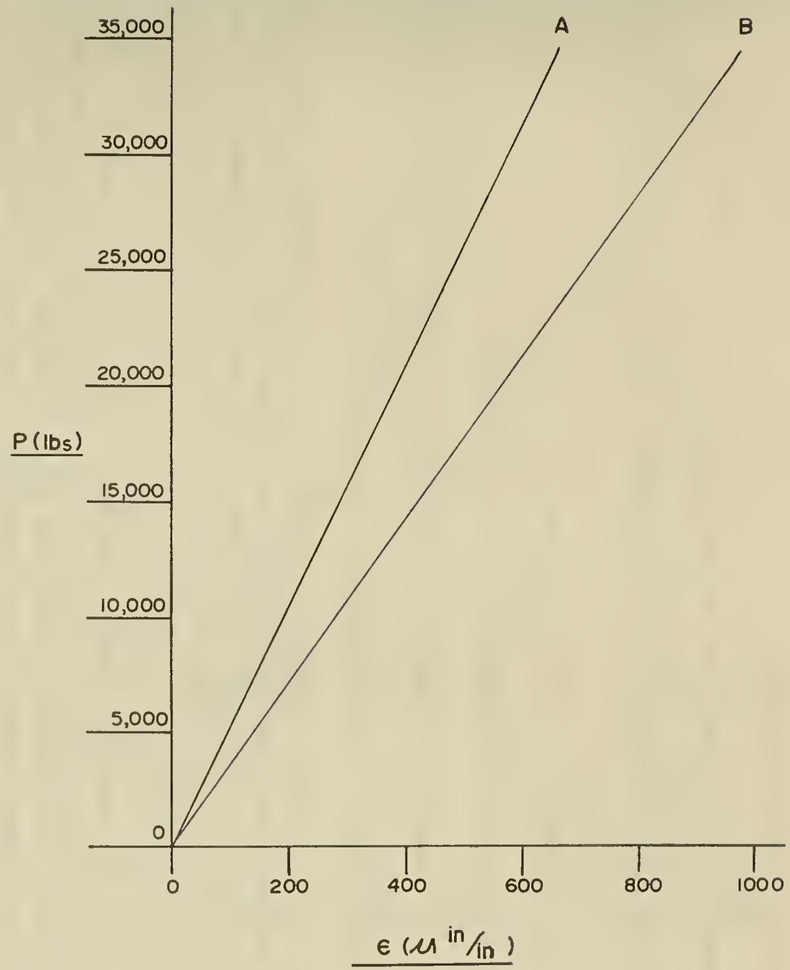


FIGURE 18. - Computer calculated strain-load curves for points A and B on test canopy.

where ε_b = bending strain, in/in,

M_e = computer calculated end moment about Z_m axis, in-lb,

c = distance in Y_m direction from member centroid to extreme fiber (1.756 in),

E = Young's modulus (29,000,000 psi),

and I_z = moment of inertia about Z_m axis (1.18 in^4).

Figure 18 gives the computer calculated strain-load curves for points A and B.

COMPARISON OF EXPERIMENTAL AND CALCULATED RESULTS

Figures 19 and 20 depict the comparisons between experimental and calculated load-deflection and load-strain curves, respectively, for the instrumented points on the test canopy. As shown in figure 20, the predicted and measured strains have a very good correlation. The predicted strains are within 5 percent of the measured strains, for any load in the elastic range.

Discrepancies far greater than 5 percent appear to exist for the load-deflection curves of figure 19. However, true comparison of measured and calculated displacements should be based upon the slopes of the load-deflection curves rather than actual values. Nonlinearity in the measured load-deflection curves exists for the first 10,000 lb of load during which time the canopy was seating into its supports. Between 10,000 and 30,000 lb, the slopes of the measured and calculated load-deflection curves agree within 5 percent.

In summary, the computer program CANOPY successfully predicted the aforementioned strains and displacements. This is not surprising since CANOPY is based upon the well-established stiffness method of structural analysis and was checked out with a variety of published example problems prior to the present canopy test.

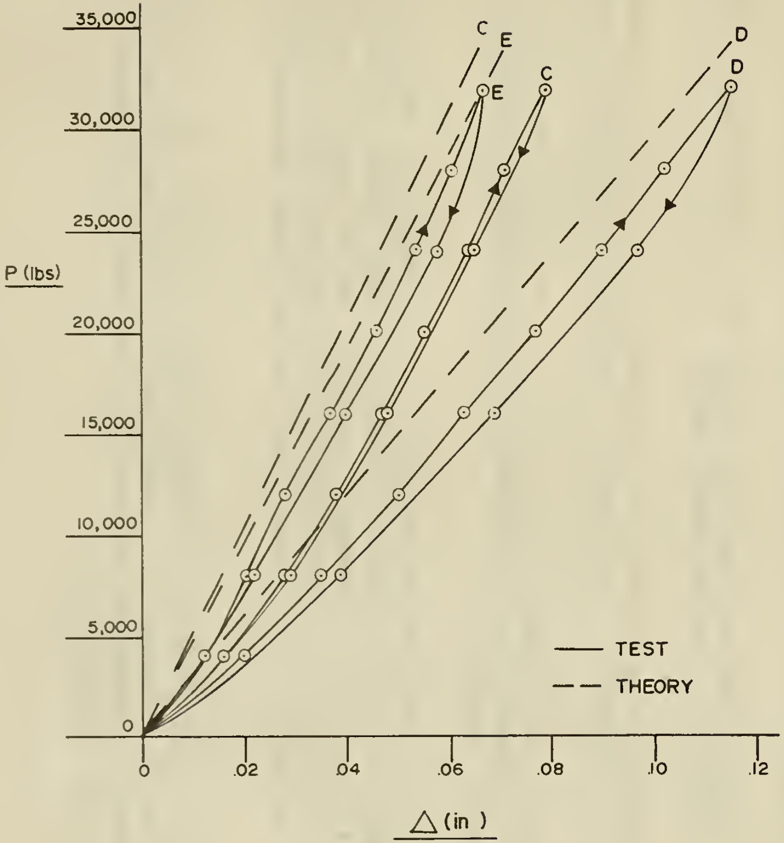


FIGURE 19. - Comparison of experimental and calculated load-deflection curves for points C, D, and E on test canopy.

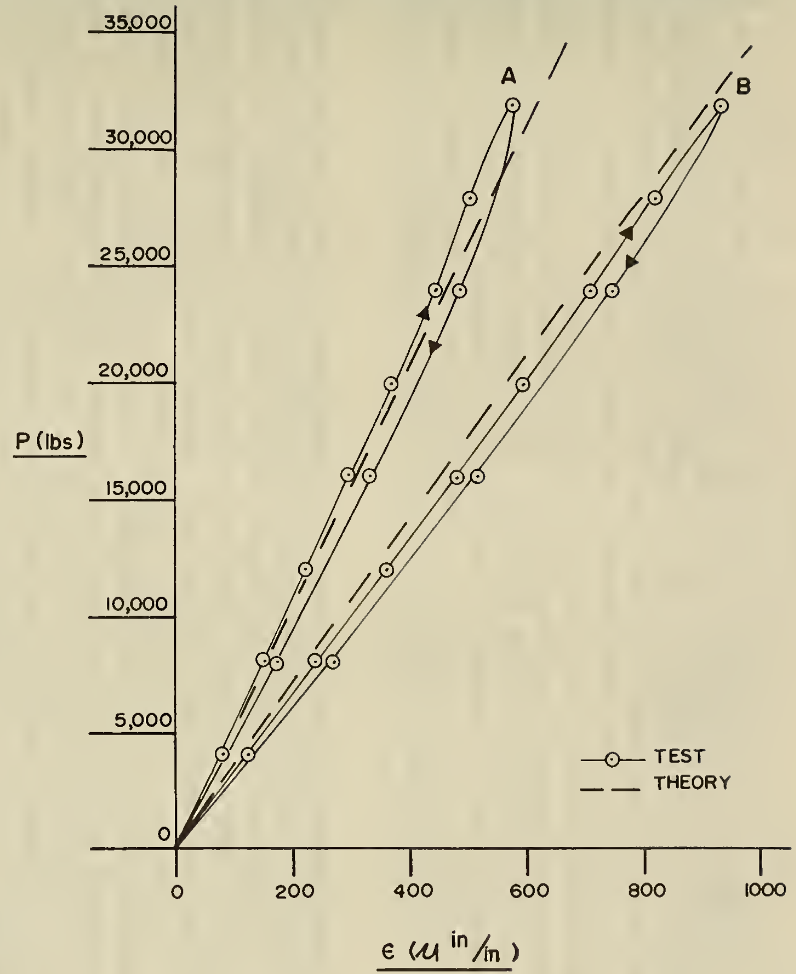


FIGURE 20. - Comparison of experimental and calculated load-strain curves for points A and B on test canopy.

DISCUSSION

In the present test, point loads and not uniform loads were applied to the canopy because of the difficulty inherent in experimentally reproducing the latter loads. As mentioned in the previous section, prior to publication, CANOPY reproduced results with the same accuracy for examples of both uniformly and point loaded beams and frames that have been published in various strength of material texts. This is to be expected because formulas used within the computer program for computation of stresses in uniformly loaded and point loaded members are based upon the same basic force-equilibrium equations. Accordingly, verification of the computer program's ability to calculate member stresses by application of point loads on a test canopy shows verification of the program's accuracy in the stress computations for uniform loads.

In the development of the overall stiffness matrix for a protective cab or canopy, uniform loads are transformed to equivalent joint loads. This idealization is inherent in the stiffness method on which CANOPY is based and does not introduce errors greater than those expected in experimental measurement or in the values used for a structural member's physical and mechanical properties. The testing of the canopy has primarily assessed the accuracy of the assumption made within the program of rigid connections between members and of the analyses performed to extend the member stiffness matrix to short, deep members (2). Point loading of the canopy challenges these two points as well as would a uniform loading. As mentioned above, the former loading is preferred because it can be experimentally applied with greater precision than a uniform loading.

When testing a cab or canopy to verify any engineering analysis, it is important to adhere to the following steps.

1. Experimentally measure the mechanical and physical properties of the members in the structure. Use these properties in analytical calculations.

2. Properly instrument the structure at the locations at which analytical values are computed or be certain that analytical values are calculated at the instrumented locations.

3. Conduct a preliminary analysis of the structure being tested to determine its elastic strength and be certain that test loads are well within this value. Results of this preliminary analysis can be helpful in suggesting points on the structure at which significant stresses and deflections can be expected and at which instrumentation could be placed although this is not necessary.

4. Record experimental data during both the load and the unload cycles, and use the averaged values for comparison with the analytical data. Be especially careful comparing measured and computed displacements as the former can contain rigid body motion.

The present test experimentally has verified the computer program CANOPY which is an excellent tool with which protective cabs and canopies can be analyzed and designed. The present report documents this verification and can be used in planning experimental tests to verify other analytical calculations on cabs and canopies.

LIST OF SYMBOLS

$\bar{A}_g$ = Mean area of tensile coupon's cross section

ACXP = Distance from X_m axis to extreme fiber at which maximum torsional stress occurs.

AXP = Cross-sectional area of structural tubing

c = Distance from neutral axis to outer fibers of structural tubing

D_e = Percent of elongation

E = Modulus of elasticity

FP = Shape factor of structural tubing

G = Shear modulus

IYP, IZP, I, I_y, I_z = Moments of inertia

IXP, I_x = Torsional moment of inertia

L = Span of beam

l_f = Final gage length of tensile coupon

l_o = Initial gage length of tensile coupon

m = Number of readings

M_b = Bending moment

M_e = Computer-calculated end moment

n = Number of applied loads

P = Applied load

P_f = Applied load at failure of tensile coupon

T(i) = Thickness of tensile coupon at point i

W(i) = Width of tensile coupon at point i

X_m, Y_m, Z_m = Member-oriented axes

X_s, Y_s, Z_s = Structure-oriented axes

Δ = Deflection

ϵ_b, ϵ = Bending strain

σ_y = Yield stress

σ_μ = Ultimate stress

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